

5           The invention is related to a current sink circuit, and in particular, to an apparatus and method for a fast settling, low-dropout-voltage current sink circuit for pulse-width modulation (PWM) light-emitting diode (LED) applications.

10           An LED is a useful device for many display and communication applications. Typically, an LED is a p-n junction made of a direct bandgap semiconductor. If the LED is forward-biased, positive carriers (i.e. holes) are injected into the n-side of the p-n junction, and negative carriers (i.e. electrons) are injected into the p-side of the p-n junction. The injected carriers recombine, causing photons to be released. Also, the  
15           wavelength of light provided by a forward-biased LED is a function of the bandgap voltage of the semiconductor. Generally, direct bandgap semiconductors are used for LEDs because radiative carrier recombination typically dominates in direct bandgap semiconductors, leading to light emission. Conversely, in indirect bandgap materials, most of the carrier recombination paths are nonradiative, generating heat instead of light.

20 According to a first approach, an LED may be driven with a DC voltage, and the DC voltage may be adjusted to adjust the brightness of the LED. According to a second approach, an LED may be driven with a high peak current having a low duty cycle, and the duty cycle of the current may be adjusted to adjust the brightness of the LED. The second approach consumes less power at a given level of brightness than the first  
25 approach.

Non-limiting and non-exhaustive embodiments of the present invention are described with reference to the following drawings, in which:

FIGURE 1 illustrates a block diagram of an embodiment of a current sink circuit;

FIGURE 2 shows a block diagram of an embodiment of the current sink circuit of FIGURE 1;

FIGURE 3 illustrates an LED circuit that includes three current sink circuits;

FIGURE 4 shows an embodiment of one of the current sink circuits and one of the LEDs of FIGURE 3;

FIGURE 5 schematically illustrates an embodiment of the current sink circuit of FIGURE 4; and

FIGURE 6 schematically illustrates another embodiment of the current sink circuit of FIGURE 4, arranged in accordance with aspects of the invention.

### **Detailed Description**

Various embodiments of the present invention will be described in detail with reference to the drawings, where like reference numerals represent like parts and assemblies throughout the several views. Reference to various embodiments does not limit the scope of the invention, which is limited only by the scope of the claims attached hereto. Additionally, any examples set forth in this specification are not intended to be limiting and merely set forth some of the many possible embodiments for the claimed invention.

Throughout the specification and claims, the following terms take at least the meanings explicitly associated herein, unless the context clearly dictates otherwise. The meanings identified below are not intended to limit the terms, but merely provide illustrative examples for the terms. The meaning of "a," "an," and "the" includes plural reference, and the meaning of "in" includes "in" and "on." The term "connected" means a direct electrical connection between the items connected, without any intermediate devices. The phrase "in one embodiment," as used herein does not necessarily refer to the same embodiment, although it may. The term "coupled" means either a direct electrical connection between the items connected, or an indirect connection through one or more passive or active intermediary devices. The term "circuit" means either a single component or a multiplicity of components, either active and/or passive, that are coupled together to provide a desired function. The term "signal" means at least one current, voltage, charge, temperature, data, or other signal.



Because voltages V1 and V2 are maintained at substantially equal voltages, the current mirror formed by transistors M0 and M1 is maintained at substantially 1:R, even if voltage V2 is relatively close to voltage V0. Accordingly, Isinkout is approximately constant, even if voltage V2 is relatively close to voltage V0. More specifically, current Isinkout is approximately constant even if V2-V0 is substantially less than the saturation voltage of transistor M0. In one embodiment, Isinkout is approximately constant even if V2-V0 is as low as approximately 150mV.

Follower circuit 120 has an input that is coupled to voltage V3 and an output that is coupled to the gate of transistor M0. Additionally, follower circuit 120 is configured to pull the voltage at the base of transistor M0 up relatively quickly after currents I1 and I2 are provided. Consequently, current Isinkout can be provided relatively quickly after currents I1 and I2 are provided.

Accordingly, current sink circuit 100 is a relatively fast-settling, low-dropout current sink.

FIGURE 2 shows a block diagram of an embodiment of current sink circuit 200. Components in current sink circuit 200 may operate in a substantially similar manner as components in current sink circuit 100, and may operate in a different manner in some ways. In current sink circuit 200, feedback circuit 210 includes current mirror circuit 230 and transistors M2-M3, and follower circuit 220 includes transistor M4.

Transistor M4 is arranged as a source follower, having a gate that is coupled to voltage V3 and a source that is coupled to the gate of transistor M0.

Feedback circuit 210 is arranged such that a current feedback loop in feedback circuit 210 maintains voltages V1 and V2 at substantially equal voltages. Further, transistors M2 and M3 are arranged such that the source voltage of transistors M2 and M3 are substantially equal if the drain currents of transistors M2 and M3 are substantially equal. Current mirror circuit 230 is configured to provide currents I1 and I2 such that currents I1 and I2 are substantially equal. Also, current mirror circuit 230 is responsive to signal BIAS.

FIGURE 3 illustrates LED circuit 380. LED circuit 380 includes battery 360, boost regulator 362, blue LED D1, green LED D2, red LED D3, and current sink circuits

301-303. Currents sink circuits 301-303 may each include an embodiment of current sink circuit 100.

Battery 360 is configured to provide voltage Vbat. Further, boost regulator 362 is configured to provide voltage Vdd from voltage Vbat. In operation, each of the LEDs D1-D3 is forward-biased. Also, each of the LEDs D1-D3 may provide light as a result of the carrier recombination that occurs when the LED is forward-biased. Blue LED D1 may provide blue light, green LED D2 may provide green light, and red LED D3 may provide red light. Also, LED circuit 380 may provide white light and/or other kinds of light by appropriately combining light from two or more of the LEDs.

In one embodiment, signals SW1-SW3 are each PWM signals. The duty cycle of signals SW1-SW3 may be adjusted to control the brightness of the light provided by LEDs D1-D3 respectively. In one embodiment, signals bias1-bias3 control the peak current in current sink circuits 301-303 respectively.

LEDs D1-D3 may each have a different voltage drop across them. In one embodiment, VDD is approximately 9.5 V, the voltage drop across LED D1 is approximately 7V, the voltage drop across LED D2 is approximately 9V, and the voltage drop across LED D3 is approximately 2V.

In one embodiment, LED circuit 380 may be used for cell phone camera flash applications, as an alternative to using a flash tube. In other embodiments, LED circuit 380 may be used for other applications.

FIGURE 4 shows an embodiment of current sink circuit 400 and LED D4. Components in current sink 400 may operate in a similar manner to similarly-named components previously described, and may operate in a different manner in some ways. Current sink circuit 400 further includes switch circuit 470 and current sink 490. In one embodiment, current sink circuit 400 also includes capacitor C0.

Signal SW may be a PWM signal. In one embodiment, signal SW is arranged to operate at a frequency of about 20 kiloHertz. Feedback circuit 410 is configured to provide currents I1 and I2 if signal SW corresponds to a first logic level, and to provide substantially no current if signal SW corresponds to a second logic level. Further, switch circuit 470 is configured to close if signal SW corresponds to a second logic level, such that node N0 is coupled to node N1 if signal SW corresponds to the second logical level.

Conversely, switch circuit 470 is configured to open if signal SW corresponds to the first logic level.

Accordingly, when signal SW corresponds to the second logic level, Isinkout is substantially zero. When signal SW changes to correspond to the first logic level,  
5 currents I1 and I2 are provided by feedback circuit 410 and switch circuit 470 is opened. When switch 470 opens, follower circuit 420 pulls node N2 up relatively quickly. Also, current sink 490 may bias follower circuit 420. In one embodiment, when signal SW changes to the first logic level, current sink circuit 400 reaches equilibrium in approximately 1  $\mu$ s.

10 When signal SW changes to correspond to the second logic level, current sink 490 pulls node N2 down relatively quickly. In one embodiment, a current sink circuit 400 includes a switch (not shown) that is coupled between nodes N1 and N2, to pull down node N2 even more quickly. In this embodiment, the switch that is coupled between nodes N1 and N2 is arranged to close if signal SW corresponds to the second logic level.

15 Additionally, LED D4 is an LED that may be used as an embodiment of LED D1, D2, or D3 from FIGURE 3. Also, voltage V2 is approximately given by  $V_{DD} - V_{D4}$ , where  $V_{D4}$  is the voltage drop across LED D4. Current sink circuit 400 is arranged to provide current Isinkout at an approximately constant voltage even if  $V_{D4}$  is fairly close to VDD.

20 Also, capacitor C0 may be arranged to increase phase margin and reduce ringing.

FIGURE 5 schematically illustrates an embodiment of current sink circuit 500. Components in current sink 500 may operate in a similar manner to similarly-named components in current sink circuit 400, and may operate in a different manner in some ways. In current sink circuit 500, switch circuit 580 includes transistor M9, transistor  
25 M13, and inverter In1. Additionally, feedback circuit 510 includes transistors M2-M3 and current mirror circuit 530. Current mirror circuit 530 includes transistors M5, M6, M10, and M11.

Transistor M11 is arranged as a switch that is responsive to signal SW. If signal SW is high, transistor M11 provides current Iref responsive to signal BIAS. Further,  
30 current mirror circuit 530 is arranged to reflect current Iref to provide currents I1 and I2 if signal SW is high.

Also, inverter Inv1 is configured to provide signal SWB in response to signal SW. Further, transistor M9 is arranged as a switch responsive to signal SW. Transistor M13 is arranged to operate as a diode.

5 Additionally, transistor M4 is arranged as a source follower having a gate that is coupled to the drain of transistor M2, and also having a source that is coupled to the gate of transistor M0.

FIGURE 6 schematically illustrates an embodiment of current sink circuit 600. Components in current sink circuit 600 may operate in a similar manner to similarly-named components in current sink circuit 400, and may operate in a different manner in some ways. Feedback circuit 610 includes transistors M2-M3 and current mirror circuit  
10 630. Current mirror circuit 630 includes transistor M5-M6, M10-M12, and M15-M16.

Transistors M11 and M12 are arranged in a current mirror arrangement to reflect current  $I_{ref}$  to provide a current at the drain of transistor M12. Also, transistors M15 and M16 are arranged in another current mirror arrangement to reflect the current at the drain  
15 of transistor M12 to the drain of transistor M16. Transistors M10, M5, and M6 are arranged in yet another current mirror arrangement to reflect the drain current of transistor M16 to provide currents  $I_1$  and  $I_2$ .

In current sink circuit 600, transistor M4 is arranged as a source follower having a gate that is coupled to the drain of transistor M12. Transistor M4 is isolated from the  
20 feedback current path. Accordingly, the voltage at the drain of transistor M2 can track the voltage at the drain of transistor M3 even if voltage  $V_2$  is relatively large. This way, current sink circuit 600 is arranged to provide a relatively constant current for  $I_{sinkout}$  even if voltage  $V_2$  is relatively large.

The above specification, examples and data provide a description of the  
25 manufacture and use of the composition of the invention. Since many embodiments of the invention can be made without departing from the spirit and scope of the invention, the invention also resides in the claims hereinafter appended.